

Predicting the clustering of X-ray clusters

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Abstract. We present a theoretical model which aims at predicting the clustering properties of X-ray clusters in flux-limited surveys for different cosmological scenarios. The model uses the theoretical and empirical relations between mass, temperature and X-ray luminosity, and fully accounts for the redshift evolution of the underlying dark matter clustering and cluster bias factor. We apply the model to the RASS1 Bright Sample and to the XBACs catalogue. The results show that the Einstein-de Sitter models display too low a correlation length, while models with a matter density parameter $\Omega_{0m} = 0.3$ (with or without a cosmological constant) are successful in reproducing the observed clustering.

1. The model

Matarrese et al. (1997) developed an algorithm to describe the clustering in our past light-cone, where the non-linear dynamics of the dark matter distribution and the redshift evolution of the bias factor are taken into account (see also Moscardini et al. 1998, 1999a,b and Suto et al. 1999). The observed spatial correlation function ξ_{obs} in a given redshift interval \mathcal{Z} is given by the exact expression

$$\xi_{\text{obs}}(r) = \frac{\int_{\mathcal{Z}} dz_1 dz_2 \mathcal{N}(z_1) r(z_1)^{-1} \mathcal{N}(z_2) r(z_2)^{-1} \xi_{\text{obj}}(r; z_1, z_2)}{[\int_{\mathcal{Z}} dz_1 \mathcal{N}(z_1) r(z_1)^{-1}]^2}, \quad (1)$$

where $\xi_{\text{obj}}(r, z_1, z_2)$ is the correlation function of pairs of objects at redshifts z_1 and z_2 with comoving separation r and $\mathcal{N}(z)$ is the actual redshift distribution of the catalogue.

An accurate approximation for ξ_{obj} over the scales considered here is

$$\xi_{\text{obj}}(r, z_1, z_2) \approx b_{\text{eff}}(z_1) b_{\text{eff}}(z_2) \xi_{\text{m}}(r, z_{\text{ave}}), \quad (2)$$

where ξ_{m} is the dark matter covariance function and z_{ave} is an intermediate redshift between z_1 and z_2 .

The effective bias b_{eff} appearing in the previous equation can be expressed as a weighted average of the ‘monochromatic’ bias factor $b(M, z)$ of objects of some given intrinsic property M (like mass, luminosity, ...), as follows

$$b_{\text{eff}}(z) \equiv \mathcal{N}(z)^{-1} \int_{\mathcal{M}} d \ln M' b(M', z) \mathcal{N}(z, M'), \quad (3)$$

where $\mathcal{N}(z, M)$ is the number of objects actually present in the catalogue with redshift in the range $z, z + dz$ and M in the range $M, M + dM$, whose integral over $\ln M$ is $\mathcal{N}(z)$. In our analysis of the two-point correlation function for X-ray selected clusters we will use for $\mathcal{N}(z)$ in eq.(2) the observed one, while in the theoretical calculation of the effective bias we will take the $\mathcal{N}(z, M)$ predicted by the model described below. This phenomenological approach is self-consistent, in that our theoretical model for $\mathcal{N}(z, M)$ will be required to reproduce the observed cluster abundance and their $\log N$ – $\log S$ relation.

For the cluster population it is extremely reasonable to assume that structures on a given mass scale are formed by the hierarchical merging of smaller mass units; for this reason we can consider clusters as being fully characterized at each redshift by the mass M of their hosting dark matter haloes. In this way their comoving mass function can be computed using an approach derived from the Press-Schechter technique. Moreover, it is possible to adopt for the monochromatic bias $b(M, z)$ the expression which holds for virialized dark matter haloes (e.g. Mo & White 1996). Recently, a number of authors have shown that the Press-Schechter relation does not provide an accurate description of the halo abundance both in the large and small-mass tails. Also, the simple Mo & White (1996) bias formula has been shown not to correctly reproduce the correlation of low mass haloes in numerical simulations. We adopt the relations recently introduced by Sheth & Tormen (1999), which have been shown to produce an accurate fit of the distribution of the halo populations in the GIF simulations.

The last ingredient entering in our computation of the correlation function is the redshift evolution of the dark matter covariance function ξ_{m} . We use an accurate analytical method to evolve ξ_{m} into the fully non-linear regime. In particular, we use the fitting formula given by Peacock & Dodds (1996).

In order to predict the abundance and clustering of X-ray selected clusters in flux limited surveys we need to relate X-ray cluster fluxes into a corresponding halo mass at each redshift. The given band flux S corresponds to an X-ray luminosity $L_X = 4\pi d_L^2 S$ in the same band, where d_L is the luminosity distance. To convert L_X into the total luminosity L_{bol} we perform band and bolometric corrections by means of a Raymond-Smith code, where an overall ICM metallicity of 0.3 times solar is assumed. We translate the cluster bolometric luminosity into a temperature, adopting the empirical relation $T = \mathcal{A} L_{\text{bol}}^{\mathcal{B}} (1+z)^{-\eta}$, where the temperature is expressed in keV and L_{bol} is in units of $10^{44} h^{-2} \text{ erg s}^{-1}$. In the following analysis we assume $\mathcal{A} = 4.2$ and $\mathcal{B} = 1/3$; these values allow a good representation of the local data for temperatures larger than ≈ 1 keV. Moreover, even if observational data are consistent with no evolution in the $L_{\text{bol}} - T$ relation out to $z \approx 0.4$, a redshift evolution described by the parameter η has been introduced to reproduce the observed $\log N$ – $\log S$ relation (Rosati et al. 1998; De Grandi et al. 1999) in the range $2 \times 10^{-14} \leq S \leq 2 \times 10^{-11}$.

Finally, with the standard assumption of virial isothermal gas distribution and spherical collapse, it is possible to convert the cluster temperature into the mass of the hosting dark matter halo (see e.g. Eke et al. 1996).

2. Results for RASS1 Bright Sample and XBACs

We applied our method to different flux-limited surveys. Here we show only the results obtained for the RASS1 Bright Sample (De Grandi et al. 1999) and for the XBACs catalogue (Ebeling et al. 1996). The application to other surveys (BCS, REFLEX and possible future space missions) is presented in Moscardini et al. (1999b).

The RASS1 Bright Sample contains 130 clusters of galaxies selected from the first processing of the *ROSAT* All-Sky Survey (RASS1) data. This sample was constructed as part of an ESO Key Programme aimed at surveying all southern RASS candidates, which is now known as the REFLEX cluster survey. The RASS1 Bright Sample is count-rate-limited in the *ROSAT* hard band (0.5 – 2.0 keV), so that due to the distribution of Galactic absorption its effective flux limit varies between 3.05 and 4×10^{-12} erg cm $^{-2}$ s $^{-1}$ over the selected area. This covers a region of approximately 2.5 sr within the Southern Galactic Cap. In Figure 1 we compare our predictions for the RASS1 spatial correlation function in different cosmological models to the observational estimates. Moscardini et al. (1999a) find that the two-point correlation function $\xi(r)$ of the RASS1 Bright Sample is well fitted by the power-law $\xi = (r/r_0)^{-\gamma}$, with $r_0 = 21.5^{+3.4}_{-4.4}$ h $^{-1}$ Mpc and $\gamma = 2.11^{+0.53}_{-0.56}$ (95.4 per cent confidence level with one fitting parameter). We considered five models, all normalized to reproduce the local cluster abundance (Eke et al. 1996) and belonging to the general class of Cold Dark Matter (CDM) models (the first three are Einstein-de Sitter models): a standard CDM (SCDM) model; the so-called τ CDM model; a tilted model (TCDM), with spectral index $n = 0.8$ and with a high (10 per cent) baryonic content; an open CDM model (OCDM), with matter density parameter $\Omega_{0m} = 0.3$ and a low-density flat CDM model (Λ CDM), with $\Omega_{0m} = 0.3$. All the Einstein-de Sitter models here considered predict too small an amplitude. Their correlation lengths are smaller than the observational results: we find $r_0 \simeq 11.5, 12.8, 14.8$ h $^{-1}$ Mpc for SCDM, TCDM and τ CDM, respectively. On the contrary, both the OCDM and Λ CDM models are in much better agreement with the data and their predictions are always inside the 1- σ errorbars ($r_0 \simeq 18.4, 18.6$ h $^{-1}$ Mpc, respectively).

The XBACs catalogue is an all-sky X-ray sample of 242 Abell galaxy clusters extracted from the *ROSAT* All-Sky Survey data. Being optically selected, it is not a complete flux-limited catalogue. The sample covers high Galactic latitudes ($|b_{II}| \geq 20^\circ$). The adopted limiting flux is $S_{\text{lim}} = 5 \times 10^{-12}$ erg cm $^{-2}$ s $^{-1}$ in the 0.1–2.4 keV band. Due to the aforementioned selection effects, the XBACs luminosity function $N(L)$ in the faint part is much lower than that obtained from other catalogues. Using a redshift evolution of the temperature-luminosity relation, we forced our models to be consistent with the number counts. For this reason we have to introduce in the models for XBACs its incompleteness $I(L)$, defined as the ratio between its luminosity function $N_{\text{XBACs}}(L)$ and $N_{\text{real}}(L)$, which is a combination of the results for RDCS at low L (Rosati et al. 1998) and for BCS at high L (Ebeling et al. 1997). The clustering properties of this

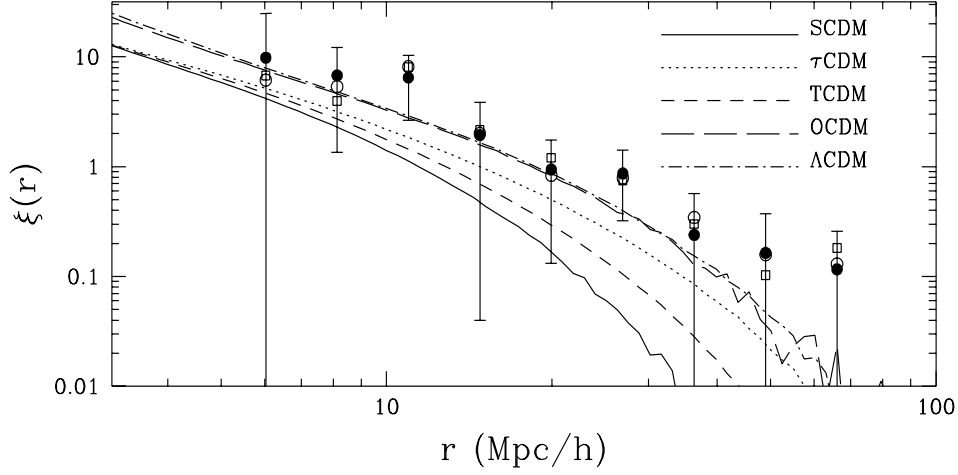


Figure 1. Comparison of the observed spatial correlation for clusters in the RASS1 Bright Sample (Moscardini et al. 1999a) with the predictions of the various theoretical models.

catalogue have been studied by different authors. Abadi et al. (1998) found that $\xi(r)$ can be fitted by the usual power-law relation with $\gamma = 1.92$ and $r_0 = 21.1^{+1.6}_{-2.3} h^{-1}$ Mpc (errorbars are 1σ). Borgani et al. (1999), who adopted an analytical approximation to the bootstrap errors, found $\gamma = 1.98^{+0.35}_{-0.53}$ and a slightly larger value of $r_0 = 26.0^{+4.1}_{-4.7} h^{-1}$ Mpc (errorbars in this case are 2σ uncertainties). Figure 2 compares these observational estimates to the theoretical predictions of the cosmological models previously introduced. Again we find that all Einstein-de Sitter models display too a small clustering. Their correlation lengths are smaller than the observational results: we find $r_0 \simeq 11, 15, 13 h^{-1}$ Mpc for SCDM, TCDM and τ CDM, respectively. On the contrary, both the OCDM and Λ CDM models give very similar results and are in better agreement with the observational data ($r_0 \simeq 20 - 22 h^{-1}$ Mpc).

3. Conclusions

We believe that the method presented here leads to robust predictions on the clustering of X-ray selected galaxy clusters. Its future application to new and deeper catalogues will provide a useful complementary tool to the traditional cluster abundance analyses to constrain the cosmological parameters.

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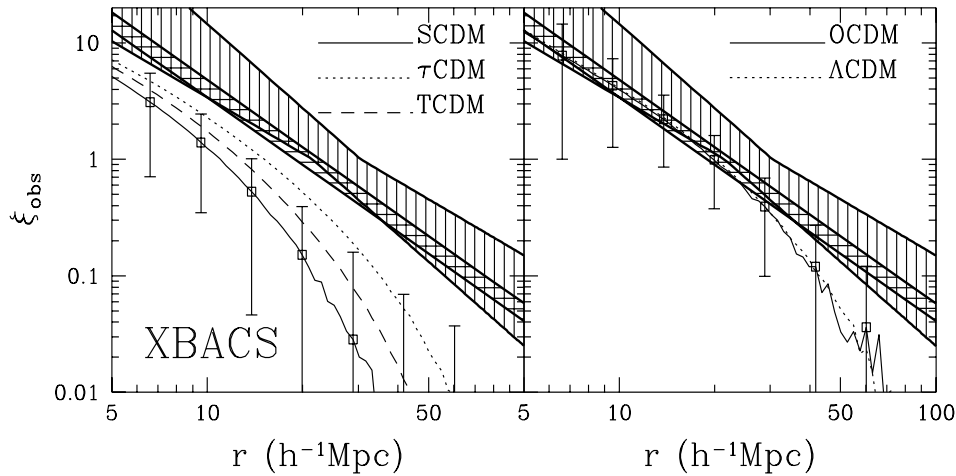


Figure 2. Comparison of the observed spatial correlation for clusters in the XBACS sample with the predictions of the various theoretical models. The horizontal shaded area refers to the ($1-\sigma$) observational estimates obtained by Abadi et al. (1998), the vertical shaded one shows the ($2-\sigma$) estimates by Borgani et al. (1999).

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